On the manoeuvring performance of a ship with the parameter of loading condition

by Katsuro Kijima*, *Member* Toshiyuki Katsuno*
Yasuaki Nakiri* Yoshitaka Furukawa**, *Member*

Summary

On the prediction of ship manoeuvring performance at the initial design stage, it is considered that a loading condition is one of the important parameters caused for the manoeuvring characteristics. For the prediction of ship manoeuvrability with high accuracy, it will be required to estimate the hydrodynamic forces acting on ship accurately in any loading conditions.

In this paper, the approximate formulae for estimating the hydrodynamic forces acting on ship in any loading conditions such as half loaded, ballast and trim by stern conditions are proposed. These approximate formulae were derived from the results of model test. The model ships used for obtaining the hydrodynamic forces are 13 ships consisting of general cargo, car carrier and RORO ships. And the model test was carried on 13 ships for fully loaded condition, on 11 ships for ballast condition and 5 ships for half loaded condition.

By comparing with the measured results of free running model test, the prediction results agree well with model test results. Therefore, this method will be useful for practical prediction of manoeuvrability for conventional ship at the initial design stage. However since those approximate formulae have been investigated on model ship, there still remain some problems to be solved such as a correlation, scale effect and so on, to predict the manoeuvring performance of full scale ship.

1. Introduction

From the viewpoint of marine safety, it is of importance to evaluate the ship manoeuvring performance at the initial design stage. The manoeuvring performance of ship, in general, will be estimated in fully loaded condition, when it is required to get the information of the manoeuvrability. IMO has been discussing on the establishment of ship manoeuvring performance standard, and the recent preliminary results of discussion have pointed out that should be dealt with fully loaded condition as the first step. The discussion of ship manoeuvring performance standard should be basically considered on fully loaded condition as the fundamental condition expressing her inherent performance for the assessment.

On the other hand, the ship generally is operated not always only in fully loaded condition, but also in half loaded condition or trimmed condition. The manoeuvring characteristics are influenced considerably by the effects of loading condition depending on ship type. For example, the turning circle as the turning ability in fully loaded condition is much larger than that in ballast condition in some cases, or the turning circle in trim by stern condition has larger in even keel condition. Furthermore, the sea trial test for new ship is mostly executed in ballast condition.

From these points, it should be considered that a loading condition is one of the important parameters to predict the manoeuvring performance. For the prediction of ship manoeuvrability with high accuracy by numerical simulation, it is required to estimate the accurate hydrodynamic forces acting on ship in any conditions. Then it becomes important to estimate the forces which correspond to the draft of the loading condition.

In this parer, the authors propose the practical prediction method for manoeuvrability at the initial design stage by using the principal particulars from the results based on captive model test for obtaining the hydrodynamic forces acting on ship.

2. Basic Mathematical Model

The mathematical model for prediction of ship manoeuvrability used in this paper has been already proposed by the authors as shown in the reference 1), that are as follows.

* Department of Naval Architecture, Kyushu University
** Graduate School, Kyushu University

$$
\left.\begin{aligned}
&(m'+m'_x)\left(\frac{L}{U}\right)\left(\frac{\dot{U}}{U}\cos\beta-\dot{\beta}\sin\beta\right)+(m'+m'_y)r'\sin\beta\\
&=X'\\
&-(m'+m'_y)\left(\frac{L}{U}\right)\left(\frac{\dot{U}}{U}\sin\beta+\dot{\beta}\cos\beta\right)\\
&+(m'+m'_x)r'\cos\beta=Y'\\
&(I'_{zz}+i'_{zz})\left(\frac{L}{U}\right)^2\left(\frac{\dot{U}}{L}r'+\frac{U}{L}\dot{r}'\right)=N'
\end{aligned}\right\} \quad (1)
$$

The superscript "′" refers to the nondimensionalized quantities as follows.

$$m',\ m'_x,\ m'_y=m,\ m_x,\ m_y/\frac{1}{2}\rho L^2 d,$$

$$I'_{zz},\ i'_{zz}=I_{zz},\ i_{zz}/\frac{1}{2}\rho L^4 d$$

$$X',\ Y'=X,\ Y/\frac{1}{2}\rho L d U^2,\ N'=N/\frac{1}{2}\rho L^2 d U^2$$

$$r'=rL/U$$

where

m', m'_x, m'_y : ship's mass, x, y axis components of added mass of ship respectively,
L : ship length,
β : drift angle,
d : draft,
U : ship speed,
r' : angular velocity,
X, Y : external force of x, y axis respectively,
N : yaw moment about the center of gravity of ship.

The external forces shown in the right hand side of the equation (1) are assumed as follows.

$$
\left.\begin{aligned}
X'&=X'_H+X'_P+X'_R\\
Y'&=Y'_H+Y'_R\\
N'&=N'_H+N'_R
\end{aligned}\right\} \quad (2)
$$

In the equation (2), the subscript "H" symbolize ship hull, "P" propeller and "R" rudder.

For the longitudinal component of the forces, the following expressions are assumed.

$$
\left.\begin{aligned}
&X'_H=X'_{\beta r}r'\sin\beta+X'_{uu}\cos^2\beta\\
&X'_P=C_{tp}(1-t_{P0})n^2D_P^4K_T(J_P)/\frac{1}{2}LdU^2\\
&K_T(J_P)=C_1+C_2J_P+C_3J_P^2\\
&J_P=U\cos\beta(1-w_P)/(nD_P)\\
&w_P=w_{P0}\exp(-4.0\beta'^2_P)\\
&\beta'_P=\beta-x'_P\cdot r',\ x'_P\simeq-0.5
\end{aligned}\right\} \quad (3)
$$

where

t_{P0} : thrust reduction coefficient in straight forward moving,
C_{tp} : constant,
n : propeller revolution,
D_P : propeller diameter,
w_{P0} : effective wake fraction coefficient at propeller location in straight forward moving,
J_P : advance coefficient,
C_1, C_2, C_3 : constant,
$X_{\beta r}=\partial^2 X/\partial\beta\partial r$, etc.

The lateral force and yaw moment acting on hull are expressed as follows.

$$
\left.\begin{aligned}
Y'_H=&Y'_\beta\beta+Y'_r r'+Y'_{\beta\beta}\beta|\beta|+Y'_{rr}r'|r'|\\
&+(Y'_{\beta\beta r}\beta+Y'_{\beta rr}r')\beta r'\\
N'_H=&N'_\beta\beta+N'_r r'+N'_{\beta\beta}\beta|\beta|+N'_{rr}r'|r'|\\
&+(N'_{\beta\beta r}\beta+N'_{\beta rr}r')\beta r'
\end{aligned}\right\} \quad (4)
$$

The terms on rudder force are assumed as follows.

$$
\left.\begin{aligned}
X'_R&=-(1-t_R)F'_N\sin\delta\\
Y'_R&=-(1+a_H)F'_N\cos\delta\\
N'_R&=-(x'_R+a_Hx'_H)F'_N\cos\delta
\end{aligned}\right\} \quad (5)
$$

where

t_R : coefficient for additional drag,
a_H : ratio of additional lateral force,
x'_H : nondimensional distance between the center of gravity of ship and center of additional lateral force ($x'_H=x_H/L$),
x'_R : nondimensional distance between the center of gravity of ship and center of lateral force ($x'_R=x_R/L$),
δ : rudder angle.

The normal force acting on rudder "F'_N" is assumed as the following expressions.

$$
\left.\begin{aligned}
&F'_N=(A_R/Ld)C_NU'^2_R\sin\alpha_R\\
&C_N=6.13K_R/(K_R+2.25)\\
&U'^2_R=(1-w_R)^2\{1+Cg(s)\}\\
&g(s)=\eta K\{2-(2-K)s\}s/(1-s)^2\\
&\eta=D_P/h_R\\
&K=0.6(1-w_P)/(1-w_R)\\
&s=1.0-(1-w_P)U\cos\beta/nP\\
&w_R=w_{R0}\cdot w_P/w_{P0}\\
&\alpha_R=\delta-\gamma\cdot\beta'_R\\
&\beta'_R=\beta-2x'_R\cdot r',\ x'_R\simeq-0.5
\end{aligned}\right\} \quad (6)
$$

where

A_R : rudder area,
K_R : aspect ratio of rudder,
C : coefficient for starboard and port rudder,
w_{R0} : effective wake fraction coefficient at rudder in straight forward moving,
γ : flow straightening coefficient,
h_R : rudder height,
U_R : effective rudder inflow speed,
α_R : effective rudder inflow angle.

3. Approximate Formulae for Hydrodynamic Coefficients

By using the above mentioned mathematical model, we will be able to know basically the manoeuvring performance of ship. This preformance can be predicted if the hydrodynamic forces acting on ship's body, propeller and rudder are estimated. Generally speaking, these hydrodynamic forces have been obtained by the model test or the data base based on the past records, and the ship manoeuvrability has been predicted by those data or the results of model test. Therefore these approaches for prediction based on such ways are a sort of the passive method for evaluation of ship manoeuvrability from viewpoint of marine safety.

For the elimination of extremely poor manoeuvrability ship, we have to consider the ship manoeuvrability at the initial design stage, that is, the element of hull form and rudder etc. should be considered positively for the manoeuvrability at the design stage. On the contrary, it is in fact that it will be very difficult to estimate exactly the hydrodynamic forces at the early stage of design under the present state.

Under these backgrounds, it may say that it will be very useful for ship design and prediction of manoeuvrability if the hydrodynamic forces acting on ship, which are needed for the numerical simulation of manoeuvring motion, are obtained as the function of ship's body shape.

In this paper, the authors propose the approximate formulae on the hydrodynamic forces with parameters of ship's main particulars for the prediction of ship manoeuvrability by means of model test.

The model ships used for obtaining the hydrodynamic forces are 13 ships consisting of general cargo, oil tanker, car carrier and RORO ships as shown in Table 1. The test was carried on 13 ships for fully loaded condition, on 11 ships for ballast condition and 5 ships for half loaded condition. The hydrodynamic forces were measured by the captive model test.

The authors obtain the following approximate formulae to estimate the forces acting on ship with her principal particulars in deep water. However it should be noticed that the following formulae were effective to apply for the conventional ship's body, especially for the conventional stern shape.

(i) For the lateral force and yaw moment coefficients in even keel condition.

$$\left.\begin{aligned}
&Y'_\beta=\frac{1}{2}\pi k+1.4C_BB/L\\
&Y'_r-(m'+m'_x)=-1.5C_BB/L\\
&Y'_{\beta\beta}=2.5d(1-C_B)/B+0.5\\
&Y'_{rr}=0.343dC_B/B-0.07\\
&Y'_{\beta rr}=5.95d(1-C_B)/B\\
&Y'_{\beta\beta r}=1.5dC_B/B-0.65\\
&N'_\beta=k\\
&N'_r=-0.54k+k^2\\
&N'_{\beta\beta}=-0.96d(1-C_B)/B+0.066\\
&N'_{rr}=0.5C_BB/L-0.09\\
&N'_{\beta rr}=-(0.5dC_B/B-0.05)\\
&N'_{\beta\beta r}=-\{57.5(C_BB/L)^2-18.4C_BB/L+1.6\}
\end{aligned}\right\}\quad(7)$$

where

$$k=2d/L$$

(ii) For the lateral force and yaw moment coefficients in trimmed condition.

The following approximate formulae should be applied for only trim by stern condition with the definition as follows,

$$\left.\begin{aligned}
&\tau=d_a-d_f\\
&d_m=(d_a+d_f)/2
\end{aligned}\right\}\quad(8)$$

where

τ : trim quantity,

d_a : draft in after perpendicular,

d_f : draft in fore perpendicular.

$$\left.\begin{aligned}
&Y'_\beta(\tau)=Y'_\beta(0)\left\{1+(25C_BB/L-2.25)\frac{\tau}{d_m}\right\}\\
&Y'_r(\tau)-(m'+m'_x)=\{Y'_r(0)-(m'+m'_x)\}\\
&\quad\times\left\{1+[571\{d(1-C_B)/B\}^2-81d(1-C_B)/B+2.1]\frac{\tau}{d_m}\right\}\\
&Y'_{\beta\beta}(\tau)=Y'_{\beta\beta}(0)\left\{1-(35.7C_BB/L-2.5)\frac{\tau}{d_m}\right\}\\
&Y'_{rr}(\tau)=Y'_{rr}(0)\left\{1+(45C_BB/L-8.1)\frac{\tau}{d_m}\right\}\\
&Y'_{\beta rr}(\tau)=Y'_{\beta rr}(0)\left\{1+(40d(1-C_B)/B-2)\frac{\tau}{d_m}\right\}\\
&Y'_{\beta\beta r}(\tau)=Y'_{\beta\beta r}(0)\left\{1+(110d(1-C_B)/B-9.7)\frac{\tau}{d_m}\right\}\\
&N'_\beta(\tau)=N'_\beta(0)\left\{1-\frac{\tau}{d_m}\right\}\\
&N'_r(\tau)=N'_r(0)\left\{1+(34C_BB/L-3.4)\frac{\tau}{d_m}\right\}\\
&N'_{\beta\beta}(\tau)=N'_{\beta\beta}(0)\left\{1+(58d(1-C_B)/B-5)\frac{\tau}{d_m}\right\}\\
&N'_{rr}(\tau)=N'_{rr}(0)\left\{1-(30C_BB/L-2.6)\frac{\tau}{d_m}\right\}\\
&N'_{\beta rr}(\tau)=N'_{\beta rr}(0)\left\{1+(48(C_BB/L)^2-16C_BB/L+1.3)\times10^2\frac{\tau}{d_m}\right\}\\
&N'_{\beta\beta r}(\tau)=N'_{\beta\beta r}(0)\left\{1+(3C_BB/L-1)\frac{\tau}{d_m}\right\}
\end{aligned}\right\}\quad(9)$$

$Y'_\beta(\tau)$, etc. mean the derivative in trimmed condition, and $Y'_\beta(0)$, etc. in even keel condition shown in equation (7).

(iii) For the longitudinal component of the forces

Relating to the longitudinal component of the forces, there are so many data base or calculation methods as well known. But on the forces in ballast or trimmed conditions, the following formulae are assumed by the results of model test in this paper.

Denoting the draft in fully loaded condition by d_F, and any draft in even keel condition by d_μ, μ' is defined as follows.

Table 1 Main particulars of model ships.

Name of Ship		A	B	C	D	E	F	G	H	I	J	K	L	M
Type of Ship		VLCC	Cargo	Cont.	Car C.	Cargo	ULCC	LNG	Cont.	Cargo	RO/RO	ULCC	VLCC	ULCC
FULL	L	2.50	2.50	3.00	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50
	B	0.436	0.408	0.435	0.482	0.419	0.466	0.409	0.386	0.376	0.367	0.555	0.408	0.500
	d_m	0.157	0.171	0.163	0.134	0.140	0.156	0.100	0.130	0.158	0.102	0.183	0.170	0.183
	C_B	0.802	0.773	0.572	0.522	0.698	0.835	0.714	0.566	0.651	0.557	0.821	0.831	0.820
HALF	d_m	0.117	0.128					0.093	0.107		0.093			
	C_B	0.782	0.746					0.707	0.540		0.537			
BALLAST	d_m	0.084	0.092	0.094	0.111	0.082	0.076	0.086	0.085	0.072	0.083	0.089		
	C_B	0.766	0.725	0.518	0.491	0.666	0.802	0.703	0.516	0.574	0.512	0.783		

$$\mu'=\frac{d_F-d_\mu}{d_F} \tag{10}$$

The longitudinal component of forces are nondimensionalized as follows.

$$\left.\begin{aligned} X'_{uu}(\mu)&=X_{uu}(\mu)/\frac{1}{2}\rho L d_\mu U^2 \\ X'_{uu}(F)&=X_{uu}(F)/\frac{1}{2}\rho L d_F U^2 \end{aligned}\right\} \tag{11}$$

where

$X_{uu}(\mu)$: longitudinal component of the forces at any draft in even keel condition,

$X_{uu}(F)$: longitudinal component of the forces at fully loaded condition

And the coefficients of longitudinal component of the forces in trimmed condition are assumed as the function of trim quantity τ as follows.

$$\left.\begin{aligned} X'_{uu}(\tau)&=X'_{uu}(\mu)\left(1+0.143\frac{\tau}{d_m}\right) \\ X'_{\beta r}(\tau)-m'_y&=\{X'_{\beta r}(\mu)-m'_y\}\left(1+0.208\frac{\tau}{d_m}\right) \end{aligned}\right\} \tag{12}$$

(iv) Rudder force and its interaction forces

The most complex and difficult factors to estimate are the interaction force coefficients between hull, propeller and rudder such as a_H, x'_H, w_{R0}, w_{P0}, and γ. But these interaction coefficients have some difficulties to estimate with high accuracy at the initial design stage. However we have to predict the ship manoeuvrability at the design stage somehow considering the inherent performance.

In this paper, these interaction coefficients are assumed preliminary as follows by using the results of free running model tests and captive model tests.

(a) The interaction coefficients a_H, x'_H are assumed as function of C_B as shown in Fig. 1

(b) The coefficient for additional drag t_R is approximately assumed by the Matsumoto[2] method as follows.

$$(1-t_R)=0.28C_B+0.55 \tag{13}$$

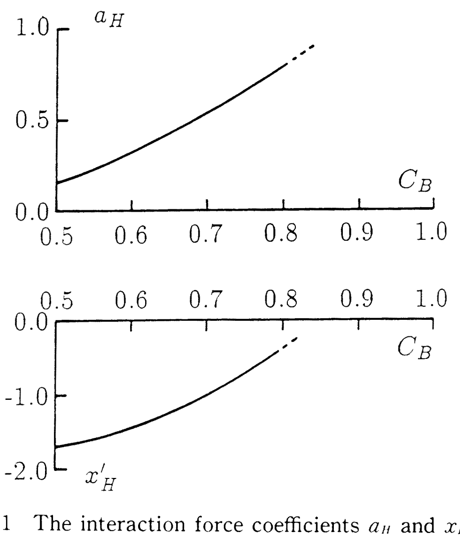


Fig. 1 The interaction force coefficients a_H and x_H.

(c) The wake fraction coefficient w_{P0} at propeller location is estimated by the results of model test by D. W. Taylor as follows.

$$w_{P0}=0.5C_B-0.05 \tag{14}$$

(d) It will be very difficult to estimate the wake fraction coefficient w_{R0} and the flow straightening coefficient γ exactly, in spite of these factors are significantly important for the manoeuvring characteristics, as the authors have shown in reference 3). On the Ship B shown in Table 1, Fig. 2 shows the turning characteristics depending on the variation of γ and w_{R0} on condition which the other coefficients used the above mentioned formulae. It can be understood that the flow straightening coefficient γ is closely related to the advance and tactical diameter of turning motion from this figure, and the normal force acting on rudder "F'_N" varies depending on the value of γ during steady turning motion. However, the wake fraction w_{R0} is connected with the turning advance, but the another turning characteristics such as tactical diameter are little affected by w_{R0}.

From these investigations, the wake fraction ratio ε and flow straightening coefficient γ are assumed as follows in this paper.

$$\left.\begin{aligned} \varepsilon&=(1-w_{R0})/(1-w_{P0})= \\ &\quad -156.2(C_BB/L)^2+41.6(C_BB/L)-1.76 \\ \gamma&=-22.2(C_BB/L)^2+0.02(C_BB/L)+0.68 \end{aligned}\right\} \tag{15}$$

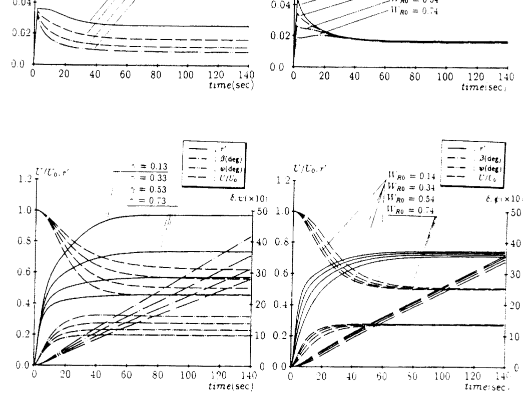
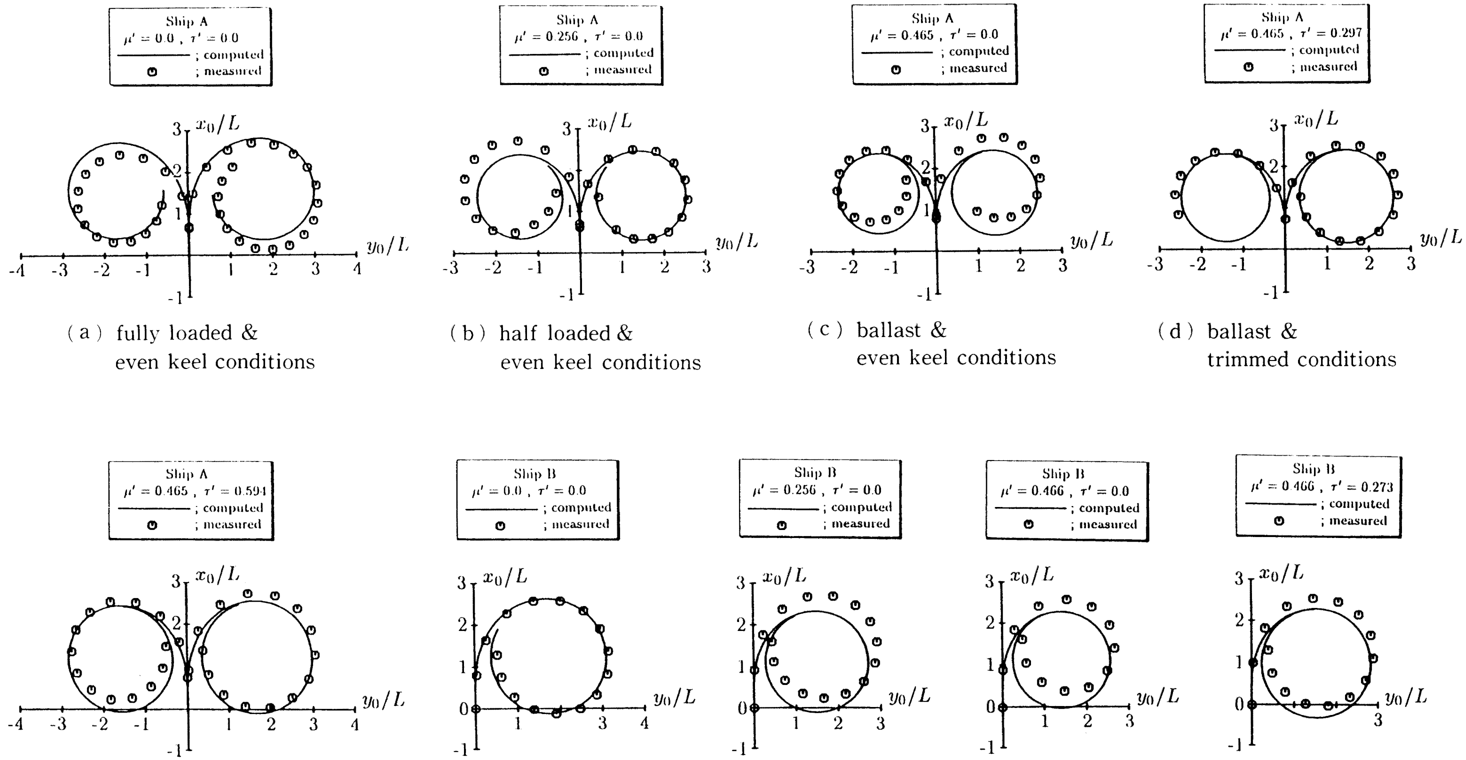


Fig. 2 Turning characteristics depending on the variation of γ and w_{R0}.



(a) fully loaded & even keel conditions

(b) half loaded & even keel conditions

(c) ballast & even keel conditions

(d) ballast & trimmed conditions

(e) ballast & trimmed conditions

(f) fully loaded & even keel conditions

(g) half loaded & even keel conditions

(h) ballast & even keel conditions

(i) ballast & trimmed conditions

Fig. 3 Turning trajectories on Ship A and Ship B due to the rudder angle 35 degrees.

4. Numerical Simulation and Discussions

Some examples predicted the manoeuvring performance of model ship by using the approximate formulae are shown in this section. The model ships used in the simulation are Ship A(VLCC) and Ship B(general cargo ship) shown in Table 1.

Fig. 3 shows the turning trajectories on Ship A and Ship B due to the rudder angle of 35 degrees in fully loaded, half loaded and ballast conditions, in even keel and trimmed conditions, where $\tau'=\tau/d_m$. Fig. 3-a, 3-b, 3-c in Ship A and Fig. 3-f, 3-g, 3-h in Ship B show the results in even keel condition respectively. Fig. 4 shows the time histories of ship speed (U/U_0, where U_0 : initial speed), drift angle (β), angular velocity (r') and heading angle (ψ) during starboard turning motion.

The simulation results of turning trajectory in even keel condition have a little differences from the measured results especially in port turn in Fig. 3-a, 3-b, and in starboard turn in Fig. 3-g, 3-h, and the time histories of angular velocity of ship during starboard turn do not agree so much with the measured results of model ship in initial turning period in both ships, but in the condition of steady turning motion the both results agree well.

The simulation on trimmed condition are shown also in Fig. 3-d, 3-e and 3-i about the turning trajectories. There are a little differences between the simulation

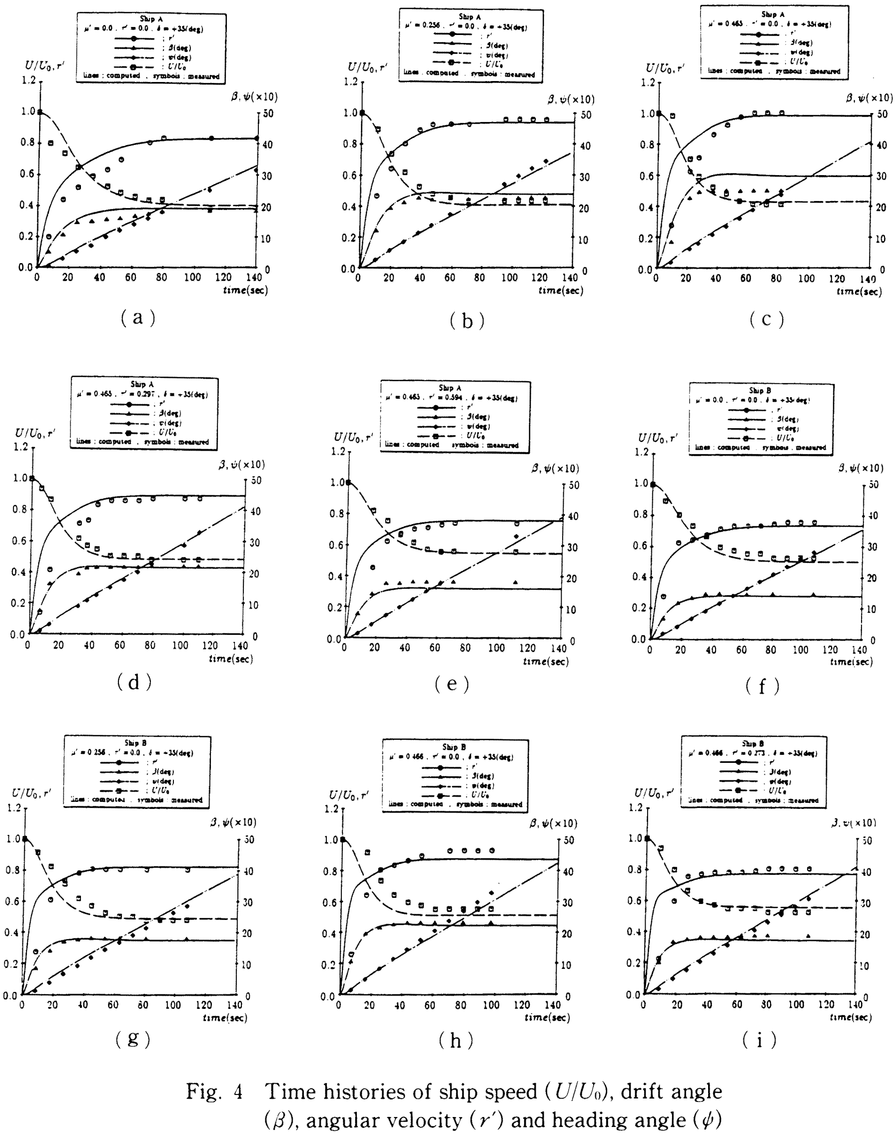


Fig. 4 Time histories of ship speed (U/U_0), drift angle (β), angular velocity (r') and heading angle (ψ) during starboard turning motion.

and measured results in angular velocity at the early moment just after rudder execution, especially in ballast condition. But the simulation results in steady turning motion agree well with the measured results in any parameters.

The spiral characteristics expressing angular velocity in steady turning motion as function of rudder angle are shown in Fig. 5, furthermore the first and second overshoot angles in 20°—20° zig-zag manoeuvres in Fig. 6 on Ship A.

From these comparisons, the simulation results based on the proposed formulae for estimating the hydrodynamic forces acting on ship approximately agree with the measured results. It may be considered that the above mentioned method will be useful for prediction of ship manoeuvrability, though there still remain some problems to be solved.

As a consequence, it is not too much to say that the significance of this method was confirmed in comparison with the prediction of manoeuvring performance of model ship. However, since this methods have been investigated about only model ships, the discussion on the prediction of manoeuvrability of full scale ship should be done much more in detail. Our final aim is to predict the manoeuvring performance of full scale ship. Needless to say, on the prediction of manoeuvrability of full scale ship by applying this method, there are some problems such as a correlation, scale effects and so on. The above mentioned method is for model ship, but it will be able to predict the manoeuvring performance of full scale ship if the interaction coefficients such as the wake fraction and the flow straightening coefficients are fully considered with high accuracy.

As a matter of course, among these interaction coefficients, there are some ones which are difficult to estimate exactly by means of theoretical way at the initial design stage. At the early stage of design in actuality, it will be not so easy to carry out the model test for estimating the hydrodynamic forces. But as the above mentioned, it will be required to predict the ship

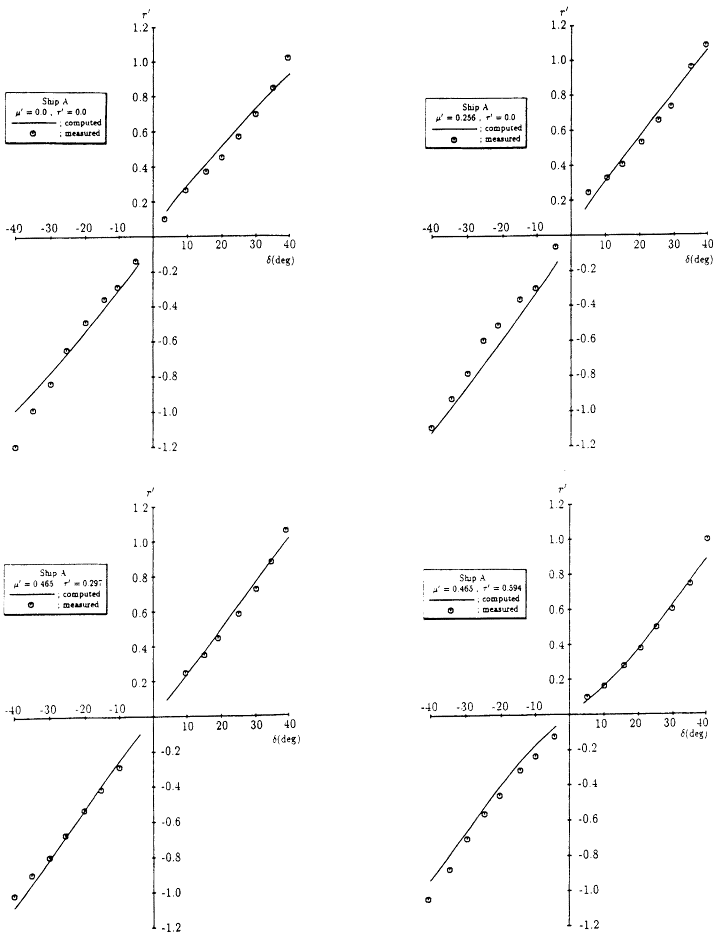


Fig. 5 Spiral characteristics as function of loading condition.

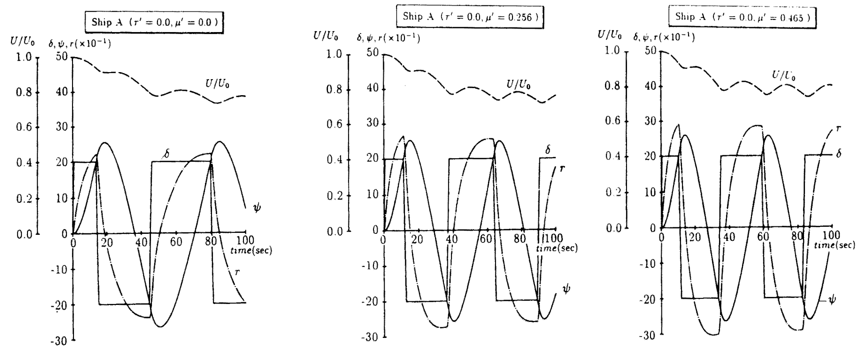


Fig. 6 The first and second overshoot angles in 20°—20° zig-zag manoeuvres.

manoeuvring performance at the initial design stage if the ship needs to satisfy the regulation of performance standard or the performance requirements. Consequently the manoeuvring performance must be considered from the stage of hull design for the marine safety.

But unfortunately, it has a little difficulty to predict the manoeuvring performance with high accuracy by considering the exact body shape of ship. Then the above method shall be used usually in conventional ship's body. For the ship with extremely different stern shape comparing with the conventional ship, for example, for a ship with a extremely poor course stability, this method will be not useful so much. For the prediction of manoeuvrability of unconventional ship such as wide beam and shallow draft, it will be necessary to collect data or to study the theoretical method which can obtain the hydrodynamic forces considering such the body shape.

5. Concluding Remarks

The authors have already proposed the estimation method of hydrodynamic forces acting on ship in fully loaded condition in deep and shallow waters. But the sea trial tests of new built ship are mostly carried out in ballast condition for dry cargo ship. Consequently we can not recognize the manoeuvring performance in fully loaded condition in detail. On the other hand, it is of importance to know the manoeuvrability in any conditions from the viewpoint of marine safety.

In this paper, for the prediction of ship manoeuvrability at the initial design stage, the authors propose the approximate formulae for estimating the hydrodynamic forces acting on ship in any loading conditions. These approximate formulae were derived from the results of model test. By comparing with the measured results of free running model test, the prediction results using these approximate formulae agree well with the model test results. But there still remain some problems to be solved to apply this method to the prediction of full scale ship. However, the authors are expecting that this approach will be useful for prediction of ship manoeuvrability at the initial design stage as the first step if the interaction coefficients such as wake fraction and the flow straightening factor are fully considered.

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